URPA-69

The Flux of Protons in the Primary Cosmic Radiation Over Fort Churchill*

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ABSTRACT

Nuclear emulsions exposed to the cosmic radiation over Fort Churchill, Manitoba, Canada (geomagnetic latitude = 73° N) at an altitude of 120,000 feet for 13 hours and 52 minutes on August 4, 1962 have been used to determine the flux of hydrogen nuclei in the primary cosmic radiation. The flux at the top of the atmosphere is found to be 978 ± 125 protons per sec per meter^2 sterad with kinetic energies greater than $375.3^{+34.7}_{-38.4}$ Mev.

INTRODUCTION

In any experiment to measure the flux of the primary hydrogen nuclei in the cosmic radiation, one is beset with the problem of albedo. The albedo is divided into two classes, the "splash" and the "reentrant" albedo. Those secondaries which move in an upward direction, into the detector constitute the "splash" albedo and are predominantly made up of high energy electrons (according to the experimental evidence presented by McDonald and Webber.[1]) The "splash" albedo particles can be distinguished from those of the primary radiation only be detectors which have directional sensitivity. The Cerenkov scintillator array of McDonald and Webber provided such an array which was able to discriminate adequately against the large background of upward moving particles.

The earth's magnetic field acts on the "splash" albedo and a portion of it will reenter the atmosphere and form the "reentrant" albedo. The Cerenkov scintillator method cannot distinguish the "reentrant" albedo from the primary particles due to the fact that the "reentrant" albedo enters the Cerenkov counter in the same direction as the primary particles.

Waddington[2] described a method of determining the flux of primary protons using nuclear emulsions which was able to eliminate the splash albedo and also to reduce the problem of the "reentrant" albedo to a certain extent in that it discriminates against non-nucleonic particles. In this method, the number of interactions or stars produced by singly charged particles in a given bolume of the emulsion is determined; these particles are required to be incident from the upper hemisphere and are assumed to be primary protons. The flux of the protons at the top of the atmosphere determined by Waddington in this way using the nuclear emulsion technique has been found to agree with that obtained by McDonald and Webber with arrays of Cerenkov scintillator counters.

In this experiment, the flux of protons having kinetic energies greater than $375.3\ ^{+34.7}_{-38.4}$ Mev in the primary cosmic radiation over Fort Churchill, Manitoba, Canada (geomagnetic latitude = 73°N) on August 4, 1962, has been determined using Waddington's method.

EXPERIMENTAL DETAILS

Flight details

A nuclear emulsion stack was exposed to the cosmic radiation over Fort Churchill, Manitoba, Canada (geomagnetic latitude = 73°N) on a stratopheric balloon launched on August 4, 1962. The plane of the emulsion stack was kept horizontal until the balloon reached its floating altitude and was then rotated through 90° so that it became vertical. The duration of flight at the ceiling altitude was 13 hours and 52 minutes with an average amount of 4.2 gms/cm^2 of residual atmosphere above the stack. The packing material contributed an additional 0.5 gm/cm^2 for this vertical geometry. The trajectory of the balloon was such that while at ceiling altitude, it maintained an almost constant latitude. The flight curve is attached as Fig. 1.

The emulsion stack consisted of 112 Ilford G-5 and K-2 emulsions 20 cm x 25 cm each of thickness 600 micron, (with a K-2 emulsion after every three G-5 emulsions). In addition, there were 19 Kodak NT-B4 emulsions (20 cm x 25 cm) of 625 micron thickness at one end of the stack (not utilized in this experiment).

Scanning procedure

Lines, all of which were within 1 cm. from the top of the stack were scanned for stars which satisfied the following criteria:

a. Each star should have at least three black and (or)grey prongs ($N_h \geqq 3$).

b. At least one prong should have a track length greater than 60 microns. (This criteria has been used to ensure that stars due to radio active imprities in the emulsion are not included).

The scanning was done in such a way that the fields of view overlapped along the lines scanned which was carried out under a total magnification of x 315; further examination was done under oil immersion at x 600 magnification.

Using the above criteria 1929 stars were observed in a volume of 0.6418×10^{-6} cubic meters.

Analysis of stars

These stars were then further carefully examined under a high magnification of x 1500 using oil immersion. Each star was examined for the number of black and grey prongs (N_h) and the number of shower tracks (N_s) associated with it. The presence of a shower track in the upper hemisphere was taken as evidence that it was the primary and was assumed to be a proton. The zenith angle of the shower track was then determined. When there was more than one shower track associated with the interaction, the zenith angles of all shower tracks were determined.

During this examination of the stars, the following additional conditions were imposed on the acceptance of these stars for inclusion in the analysis:

a) Only those stars which had $N_h \gtrsim 5$ were accepted in order to have a very high scanning efficiency.

b) Only those stars which lay in the region excluding 30 microns from air and 30 microns from glass were accepted.

c) Only those stars which had a shower track in the upper hemisphere with zenith angle less than 60^o with respect to the vertical direction were accepted.

Identification of primary particles

When a star had more than one minimum track associated with it, it was difficult to decide which track represents the primary particle. In stars with three or more associated minimum tracks, the primary track is taken as that which results in the least sum of the angles that the other minimum tracks make with the direction of the assumed primary. For stars with two minimum tracks, one of which fulfulls our criterion, a weight was given.

A total number of 123 stars with $N_h \gtrsim 5$, each of which had a minimum ionizing track in the upper hemisphere with zenith angle less than 60^o were obtained. After giving weight to some of the stars, the total corrected number was 112.5.

Correction for scanning efficiency

The efficiencies of the two scanners who worked in this experiment were found to be 97% and 89% respectively. The number of stars became 123.6 after correcting for scanning efficiency taking events up to a maximum zenith angle of 60^o.

Efficiency of detection of the primary particle

Assuming an isotropic distribution of zenith angles for the incident primary particles,[3] the zenith angle distribution of the number of stars per unit solid angle must give an indication as to whether some of the minimum tracks due to primary particles have been missed or not. The zenith angle distribution of the number of particles per unit solid angle, given in Fig. 2, indicated that some of the particles entering with zenith angles between 45° and 60° have been missed. Hence, it is not reasonable to expect the flux, calculated with events up to a zenith angle of 60°, to give a result consistent with the expected value.

The distribution in Fig. 3 considers only events up to a maximum zenith angle of 45°. This distribution agrees fairly well with the expected distribution. It thus seems reasonable to calculate the flux using the data available including tracks only up to a maximum zenith angle of 45°.

Background correction

The stars obtained in this experiment include background stars which were recorded during the entire life of the stack before the flight. The procedure adopted to eliminate the background stars was as follows: In most of the stars, it was possible to find at least one track which went up to the glass or air surface without stopping. If such a track continued in the next plate also, it was evident that the star had been produced during the flight for the stack was reshuffled from storage condition while assembling for the flight configuration; where the track could not be traced in the adjacent plate, the star must have been produced during storage. In 100 stars which were examined, only one star was found to have been produced in storage. Hence the correction for storage

Ascent and descent corrections

It is not really necessary to apply an ascent correction in this experiment as the emulsion stack was kept horizontal until it reached the ceiling altitutde and then rotated through 90^o. However, it is still desirable to work out a rough estimate of the correction on account of the fact that particles coming at large zenith angles during the ascent might satisfy our zenith angle criteria.

The correction can be worked out by making use of the fact that the flux is attenuated with an attenuation length of about 120 gm per cm^2 of air;[4] neglecting geometrical factors, this would yield an estimate as follows.

The package rises in ascent such that the altitude (in gms per cm^2) as a function of time is $h(t) = 1000 - \alpha t$ where $\alpha = \frac{1000 - h_o}{\Delta\tau}$ gm/cm^2 sec and $\Delta\tau$ is the time taken to ascend to h_o, the floating altitude. Then an approximate factor taking into account both the intensity variation with altitude and the time of ascent is given by

$$\frac{2\pi I_o}{2\pi I_o T_{Alt}} \int_0^{\Delta\tau} dt \, \exp\left(-\frac{(1000 - \alpha t)}{\lambda}\right)$$

where $T_{alt.}$ = time spent at the ceiling altitude. Evaluation gives the correction factor as 0.01841 (1.8%). The descent correction can be estimated in a similar fashion and turns out to be 0.6%.

Correction for the overlying atmosphere

The flux value calculated directly from the experiment has to be corrected for the effect of the atmosphere over the floating altitude in order to get the flux at the top of the atmosphere.

Waddington[2] has constructed growth curves from theoretical models. If $J_p(x,\theta)$ is the flux of primary protons and secondary protons produced by primary protons at a vertical depth x and zenith angle θ and if J_o is the flux of primary protons at the top of the atmosphere, then

$$J_p(x,o) = J_o\, e^{-\frac{x}{\lambda}} \left[1 + \frac{n_1 x}{\lambda_p} + \frac{n_1 n_2 x^2}{2!\,\lambda_p^2} + \cdots \right]$$

where λ_p is the interaction mean free path of protons in air and n_1, n_2 --- are the multiplicities in the first, second, . . . interactions. Without going to the growth curves and obtaining a graphical solution of $J_p(x, 0)/J_o$ as done by Waddington, we assume a two stage process with $n_1 = 1.5$ and $\lambda_p = 100$ gm/cm^2 and the ratio $J_p(x, 0)/J_o$ can be computed; $J_p(x,0)$ is the integral flux from 0 to θ_{max} (the maximum angle accepted). Here, instead of x, the mean value $x/\cos\theta$ is used which is $\sum \frac{x/\cos\theta}{N}$ where the summation extends over the zenith angle values of all the different primary tracks whose total number is N. This value is found to be 5.61 gm/cm^2. Using this value for x in the relation for $J_p(x,o)/J_o$ and taking the first two terms within brackets only $J_p(x,o)/J_o$ becomes 1.023 and hence $J_o = J_p(x,o)/1.023$.

In addition to this correction, another correction for protons entering into the atmosphere from heavier nuclei (in which they are bound before entering the atmosphere) has to be applied. The relation derived by Waddington[2] assuming that these bound nuclei are in the form of α particles only is

$$J_\alpha(x,o) = 2 J_{\alpha o} \frac{\lambda_p}{\lambda_p - \lambda_\alpha} \left[e^{-\frac{x}{\lambda_p}} - e^{-\frac{x}{\lambda_\alpha}} \right]$$

where λ_α is the interaction mean free path of α particles in air, assumed to be 1/2 λ_p and $J_{\alpha o}$ is the assumed flux of

α particles at the top of the atmosphere.

In this case also $J_\alpha(x, 0)$ can be approximated by taking the value of x as $\sum \frac{x\ J\ sec\ \theta}{N}$. J_o is taken to be 14% of the proton flux which is determined later as 1004 $\pm$ 23 per sec per met^2 per sterad. Hence $J_{\alpha o}$ = 141 and with λ_p = 100 gm/cm^2 and λ_α = 50 gm/cm^2, $J_\alpha(x,0)$ = 26. It can therefore be taken that about 26 protons had entered, bound in x nuclei in the flux computed in the experiment. This number has to be subtracted from the flux finally determined from the data.

Correction for stars with $N_h < 5$

No measurements were made on stars with $N_h < 5$ and to correct the data for those stars which have been produced by primary protons, the experimental data available on the interactions produced in nuclear emulsions by artificially accelerated protons is used.

The star size distribution for 1570 stars is published by Waddington(5) from the data of Wizler et al; Rajopadhaye, Aly and the CERN group,and gives a correction factor of 1.74 $\pm$ 0.04 for the ratio $\frac{\text{total number of stars}}{\text{number of stars with } N_h \geq 5}$; this has been used in this experiment to calculate the flux from stars with $N_h < 5$. Fig. 3 shows the star size distribution obtained in this experiment normalized at N_h = 5.

Results

The number of stars, after correcting for scanning efficiency, was 96.7 taking only those up to a maximum zenith angle of 45°. On correcting for storage, this becomes 95.8. This, when divided by 1.023 for $J_o = \frac{J_p(x,o)}{1.023}$ gave 93.7. On applying an ascent correction of 0.6% the number becomes 91.4. This will have to be multiplied by 1.74 $\pm$ 0.04 to correct for stars with $N_h < 5$. The primary flux is related to that observed as:

$$\text{Flux} = \frac{\lambda \, \Delta N}{\Delta V \, \Delta t \, G}$$

The value of λ, the interaction mean free path of protons in emulsion is taken as (37.2 $\pm$ 0.8) cm.

N = 91.43 x (1.74 $\pm$ 0.04) particles

ΔV = Volume of emulsion = 0.6418 x 10^{-6} cubic meters

G = Geometrical factor for 45^{o} = 1.8402 sterad

Δt = 4.992 x 10^{4} secs.

Flux = 1004 $\pm$ 125 particles per sec per met^2.

From this number, 26 particles per sterad have to be subtracted as a correction for protons entering the atmosphere bound in nuclei. Hence the flux finally becomes 978 $\pm$ 125 particles per sec per m^2 per sterad.

Discussion of results

From the neutron monitor data available for August 4, 1962, it is possible to arrive at an approximate value of the proton flux to be expected over Fort Churchill on that day.

The neutron count over Climax (Colorado) on August 4, 1964, was 3073.8. The ratio of neutron count rate over Mt. Washington is 2.76 $\pm$ 0.08 as given by Webber.(6) Hence, the count rate over Mt. Washington on that day should have been 2226 $\pm$ 70. It is possible to construct a curve relating intensity of protons of rigidity over 2 BV corresponding to the minimum energy of protons and the neutron count rate over Mt. Washington from the curves given by Webber.(6) From the curve constructed (Fig. 5) the proton flux corresponding to neutron count of 2226 $\pm$ 70 is 1260 $\pm$ 120 particles. This flux is of rigidity over 2 BV or total energy over 1.3 Bev. But the minimum energy of protons in this experiment is $(1.313 {}^{+.038}_{-.035})$ Bv. Assuming the power law $N(>E) = KE^{-\gamma}$ where γ has been taken as 1.4, it is calculated that the flux of proton over $(1.3.3 {}^{+.038}_{-.035})$ Bv on the day of flight is $(1243 {}^{+146}_{-114})$ protons per meter^2 per sterad. The agreement is considered satisfactory.

ACKNOWLEDGMENT

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4. A. W. Wolfendale Cosmic Rays, 125 (1963).

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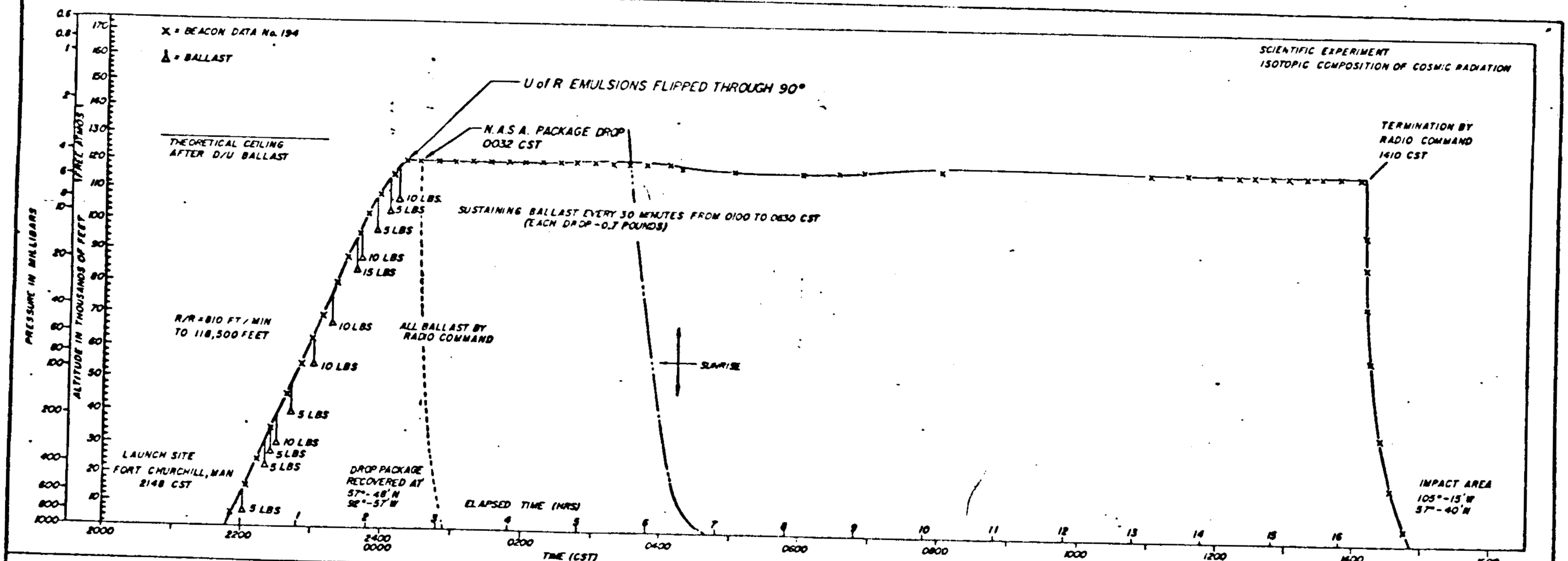


FLIGHT No. 1018-N

DATE - 4 AUGUST 1962

FOR - PROJECT 127

UNIVERSITY OF ROCHESTER

DR. KAPLON

BALLOON - TYPE - 2333-541-8201

VOL - 3 MILLION CU. FT.

MAT'L - .75 MIL POLY

WT - 436.0 LBS

LOAD FACTORS - PAYLOAD - 341.0 LBS

GROSS LD - 799.5 LBS.

FREE LIFT - 79 LBS = 10%

BALLAST - 110.0 LBS

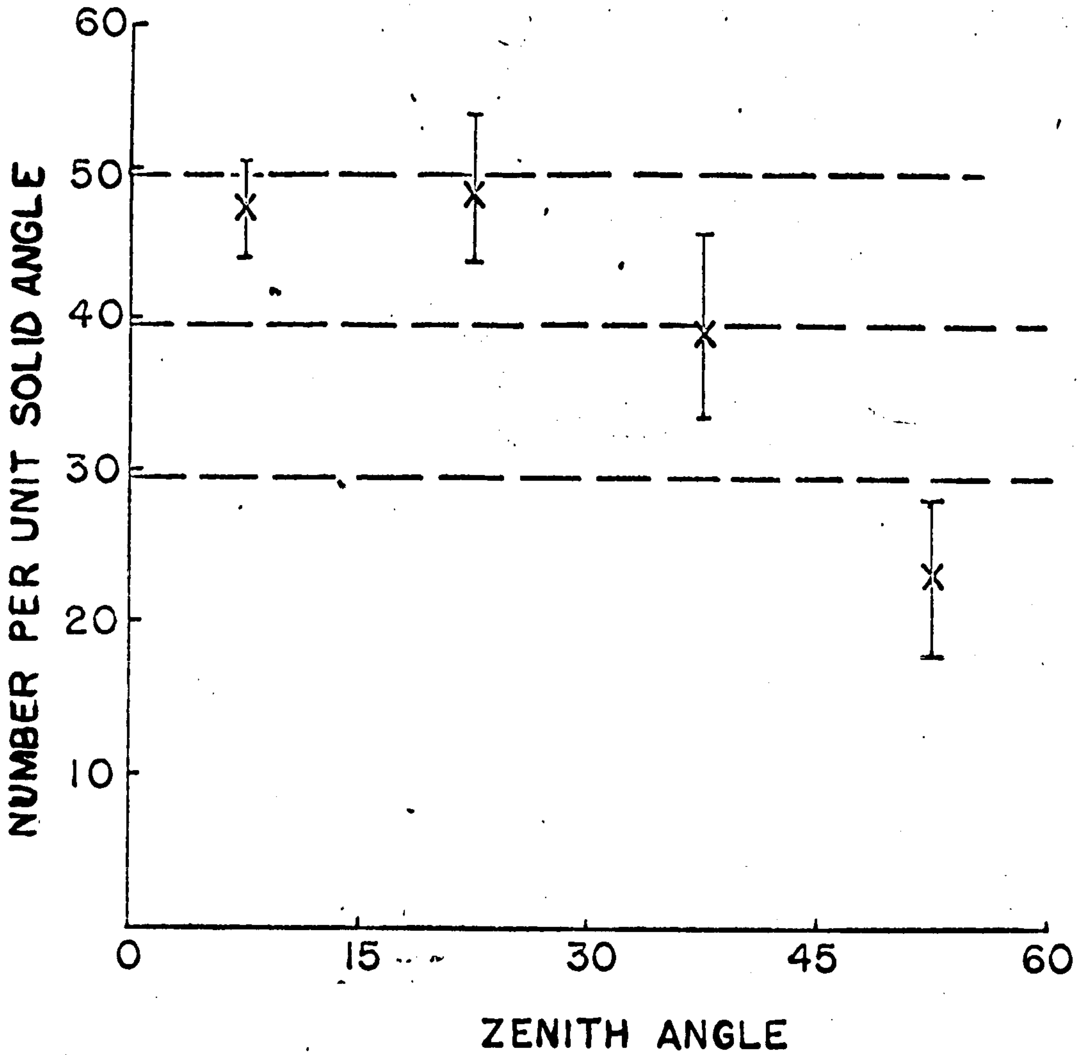
FROM - RAVEN INDUSTRIES Inc.

DRWG. NO. 2X-1965

DATED - 23 AUGUST 1961

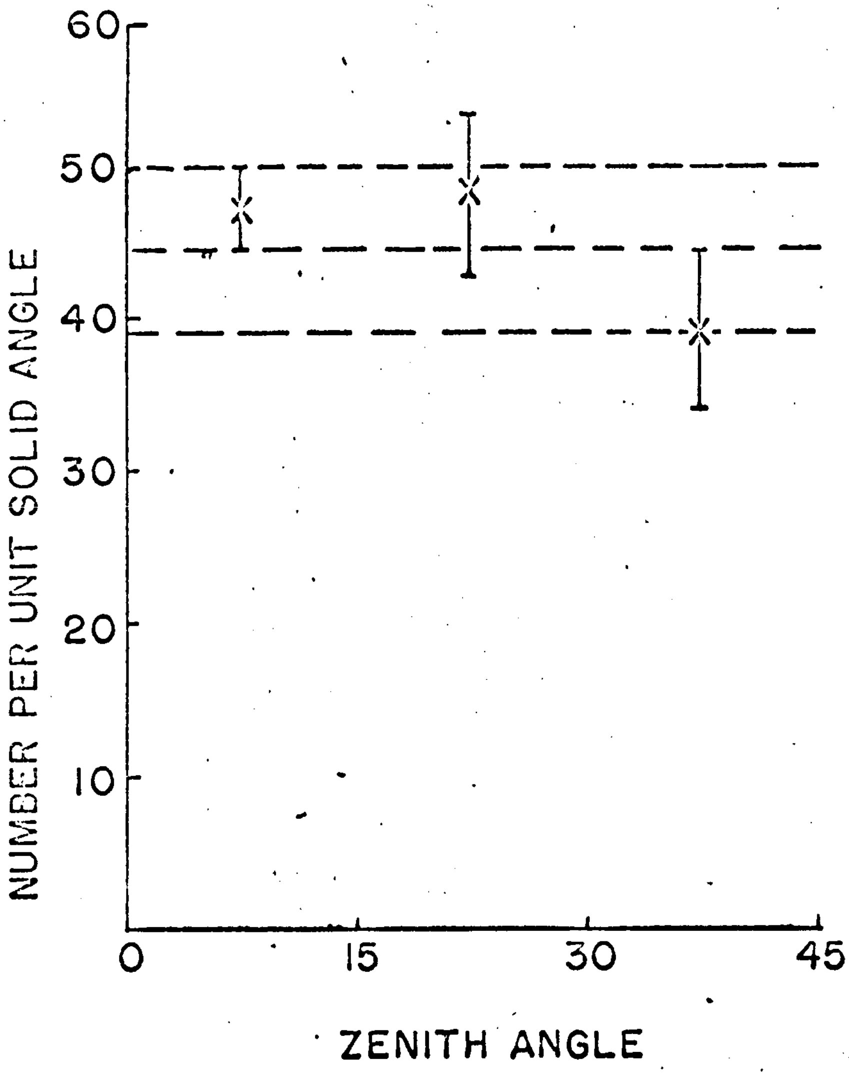
Fig 1

STACK II



NUMBER PER UNIT SOLID ANGLE
60
50
40
30
20
10
0
15
30
45
60
ZENITH ANGLE

Fig 2



60
50
40
30
20
10
NUMBER PER UNIT SOLID ANGLE
0
15
30
45
ZENITH ANGLE

Fig 3

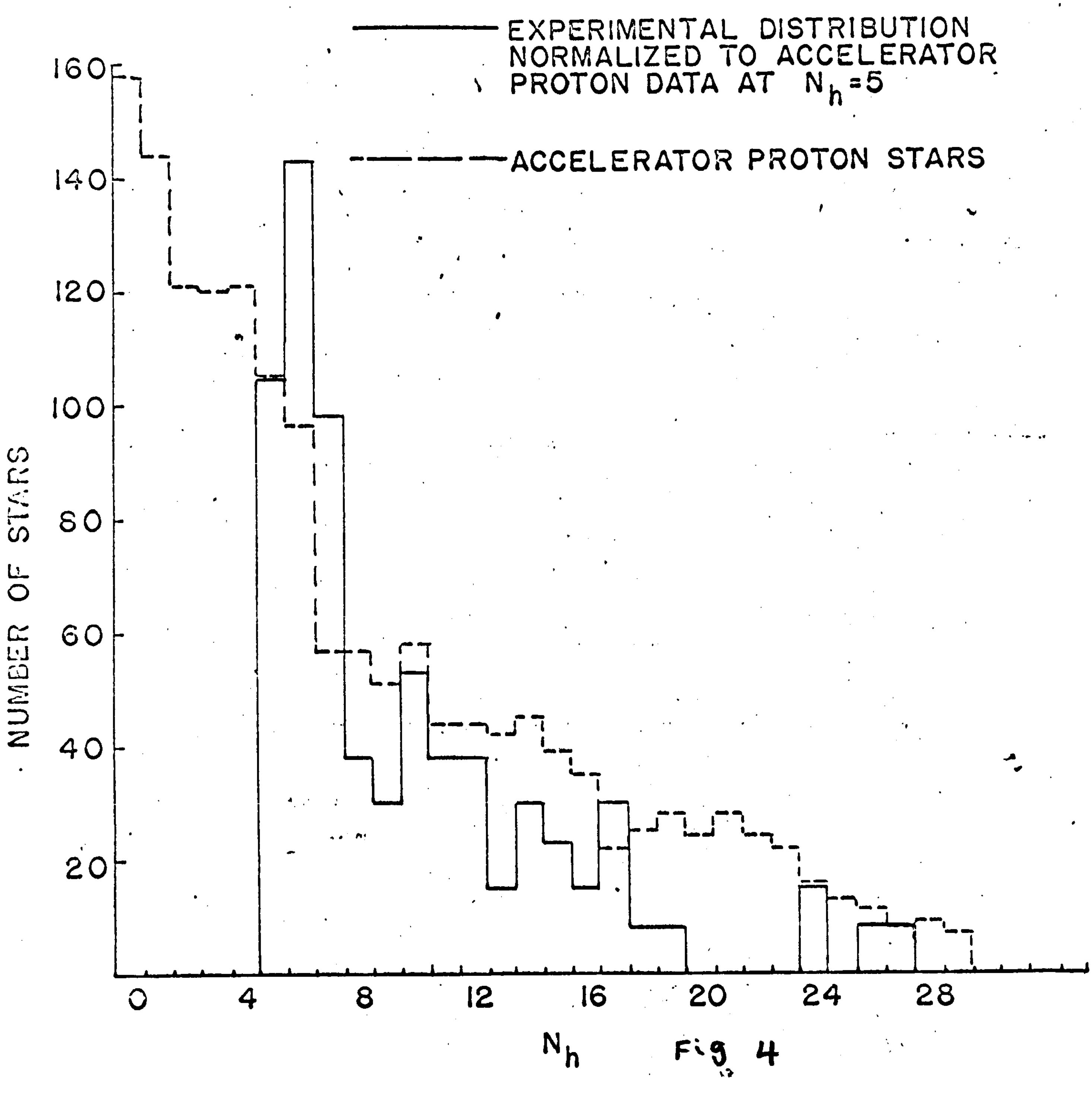

EXPERIMENTAL DISTRIBUTION NORMALIZED TO ACCELERATOR PROTON DATA AT N_h=5
ACCELERATOR PROTON STARS
NUMBER OF STARS
160
140
120
100
80
60
40
20
0
4
8
12
16
20
24
28
N_h

Fig 4

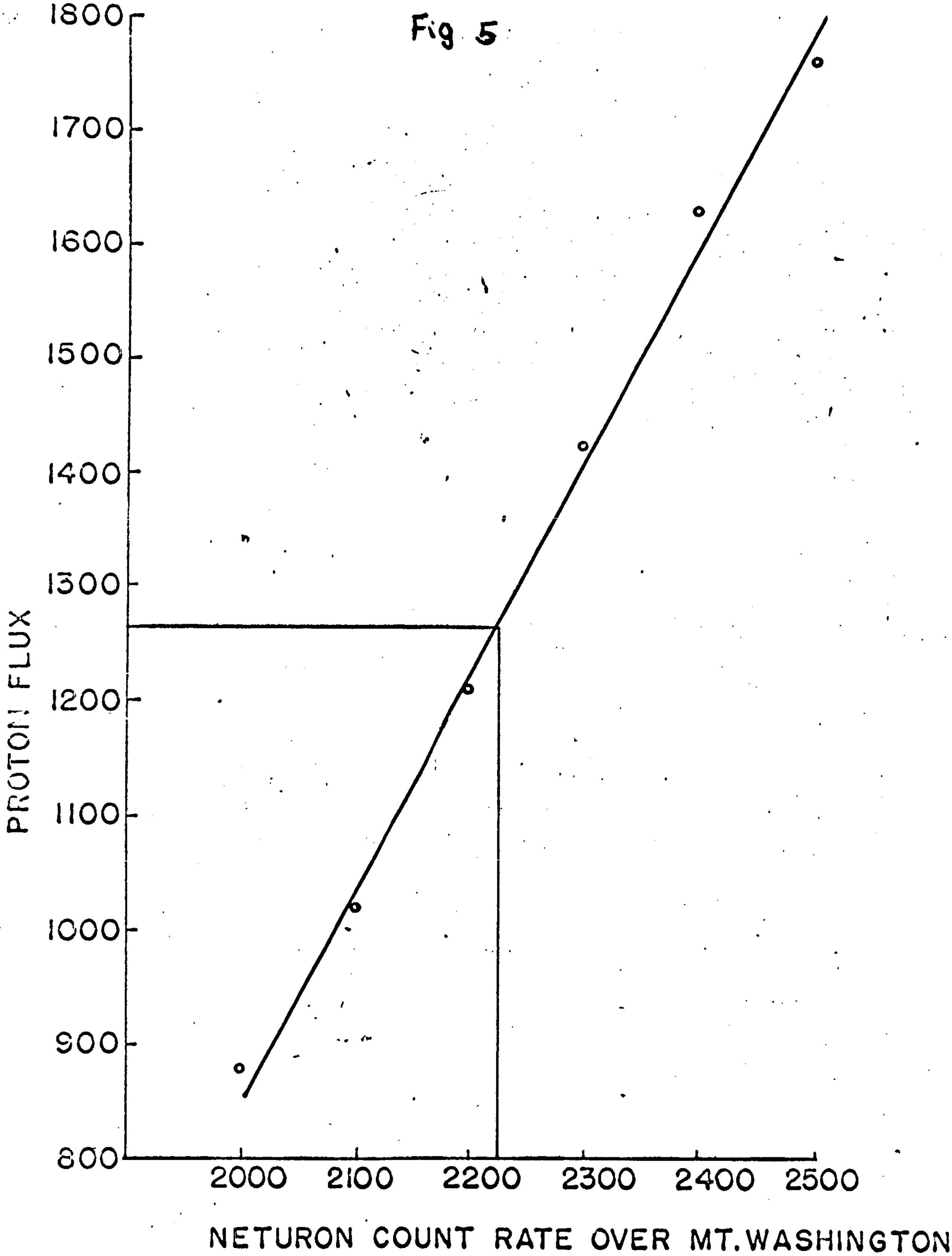


Fig 5
PROTON FLUX
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
2000
2100
2200
2300
2400
2500
NETURON COUNT RATE OVER MT. WASHINGTON